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Planet ingestion on a pre-MS star

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Abstract. We performed a theoretical study of the main effects of planet ingestion on the characteristics (structure and surface chemical composition) of a pre-main-sequence star similar to the Gamma Velorum cluster member 2MASS J08095427-4721419, a star which shows a peculiar over-abundance of metals with respect to the other cluster members. We investigated in detail the effects on the star of changing the characteristic of the accretion episode, in particular the age at which the planet ingestion occurs, the planet mass and its chemical composition. We found that depending on the characteristic of the ingested planet a large variation of the total surface metallicity of about 10-35% can be achieved, which leads to a deeper convective envelope, lower effective temperature and redder colours.

1. Introduction

In a recent paper, Spina et al. (2014) observed a star 2MASS J08095427-4721419 (hereafter #52) in the Gamma Velorum cluster that shows a peculiar surface elements abundance if compared to the other cluster members. In particular they measured a large over-abundance of iron, Δ[Fe/H]$\approx$ +0.127 dex, and of other refractory elements (e.g. Mg, Al, Sc, Ti, V and Co). Spina et al. (2014) and Spina et al. (2015) suggested that such a peculiar chemical pattern, which is similar to that expected in a protoplanetary disc, might be originated by an episode of planet engulfment. Following this suggestion, Tognelli et al. (2016) analysed in details the effect of a planet ingestion on a the chemical composition and structure of a pre-MS star similar to #52. Here, we briefly summarised the main result of such an analysis.

2. The accretion model results

We computed stellar models using the recent version of the Pisa stellar evolutionary code as described in detail in Tognelli et al. (2016) which allows to consistently follow the effect of a mass accretion episode, i.e caused by a planet engulfment.

The planet ingestion episode depends on several unknown quantities such as the age of the star t_0 when the planet is ingested, the chemical composition $\{X_i^p\}$ (mass fractional abundance of the i-element) and the mass M_p of the planet. The constrains available for the present analysis are the initial chemical composition of the star, which have been assumed to be equal to that of the other cluster members ([Fe/H]^{cl} = -0.107), and the observed surface [Fe/H]$^{\#52}$ = $+0.02$ of the star (after the accretion). In addition, we fixed the stellar mass to 1.2 $M_\odot$ which well reproduce the position of #52 in the Colour-Magnitude diagram at the estimated cluster age (about 15 Myr, see Jeffries et al. 2014). In Tognelli et al. (2016) we showed that it is possible to determine the value of the ingested planet as a function of t_0 and $\{X_i^p\}$ assuming a full and instantaneous mixing of the matter accreted with that present

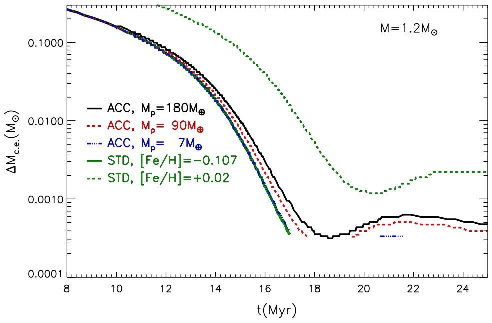

Fig. 1. Temporal evolution of $\Delta M_{c.e.}$ for models with and without (standard, STD) planet ingestion episode (see text). For the standard case we show the models with the initial [Fe/H]=[Fe/H]^{cl} and, for comparison, also that with [Fe/H]=[Fe/H]$^{\#52}$.

in the convective envelope of the star. The mass of the ingested planet required to reproduce the observed [Fe/H]$^{\#52}$ is given by the following expression,

$$\frac{M_p}{\Delta M_{c.e.}} = \frac{X_H \times 10^{[Fe/H]^{\#52}+\beta} - X_{Fe}}{X^p_{Fe}} \tag{1}$$

where, $\beta = m_H/m_{Fe} - 12 + \log \epsilon_{Fe,\odot}$ [1], X_H, X_{Fe} and $\Delta M_{c.e.}$ are respectively the abundance of hydrogen, abundance of iron and mass inside the stellar convective envelope before the ingestion episode and X^p_{Fe} is the iron contained into the planet. To be noted that the age t_0 does not appear explicitly in eq. (1) but it is contained in $\Delta M_{c.e.}$. Indeed, as well known (see Fig. 1), the extension of the convective envelope (thus $\Delta M_{c.e.}$) strongly depends on the stellar age and, consequently, on the adopted t_0. Being interested in analysing the effect of the accretion properties on the star, we selected three values for t_0, namely 10, 12 and 15 Myr. Concerning the planet chemical composition, we investigated two cases: 1) in one case we assumed that the accreted matter has exactly the same metal relative abundances than that used for the star and 2) in the other we used a metal distribution more similar to that of the Earth. In the first case we adopted the metal distribution by Asplund et al. (2009, AS09) with matter constituted mainly by O (43%), C (18%), Fe (10%), Ne (9%), Mg, N and Si (5%), the same used for the star, while in the second case we used the Earth chemical composition as given by Javoy et al. (2010, JK10) with matter mainly constituted by Fe (33%), O (31%), Si (19%) and Mg (13%). In both the cases we assumed that the planet is constituted only by metals ($Z_p = 1$). The two mixtures strongly differs in the iron content which is the quantities that directly affects the final [Fe/H] of the star after the accretion. In particular the JK10 iron content is about 3.4 times larger than that of the AS09 mixture. This directly affects the derived M_p value, as clearly visible from eq.(1). Indeed, the right side of eq.(1) depends only on the planet iron content as the [Fe/H]$^{\#52}$ is fixed by the observation. Thus, at a given age t_0 (that fixes $\Delta M_{c.e.}$), the ratio between the mass of the ingested planet and the mass in the convective envelope depends only on the amount iron contained in the planet. In particular, such a ratio is larger if the AS09 mixture (iron-poor) is adopted for the planet instead of the JK10 (iron-rich). The M_p values we derived to reproduce the observed [Fe/H]$^{\#52}$ are 180 $M_\oplus$ (t_0 = 10 Myr), 90 $M_\oplus$ (t_0 = 12 Myr) and 7 $M_\oplus$ (t_0 = 15 Myr) if the AS09 planet chemical composition is used, which reduces to 53 $M_\oplus$ (t_0 = 10 Myr), 26 $M_\oplus$ (t_0 = 12 Myr) and 2 $M_\oplus$ (t_0 = 15 Myr) if the JK10 mixture is adopted. To be noted that, the ingested planet mass reduces by increasing t_0 because of the dependence of $\Delta M_{c.e.}$ on t_0.

Once the planet has been ingested, it is rapidly destroyed and mixed with the matter contained into the convective envelope. This causes a variation of the abundances of all the chemical elements, thus leading to a change in the total surface metallicity of the star. The amount of such a variation depends on the amount of the accreted matter, i.e. on M_p. It is possible to derive a simple expression to estimate the new value of the metallicity Z^{new} after the accretion process (see Tognelli et al. 2016),

$$Z^{new} \approx Z + Z_p \frac{M_p}{\Delta M_{c.e.}} \tag{2}$$

Using the AS09 and JK10 mixture, we obtained a variation of the total surface metallic-

[1] $\epsilon_{Fe,\odot}$ is the iron to hydrogen numerical abundance ratio in the Sun.

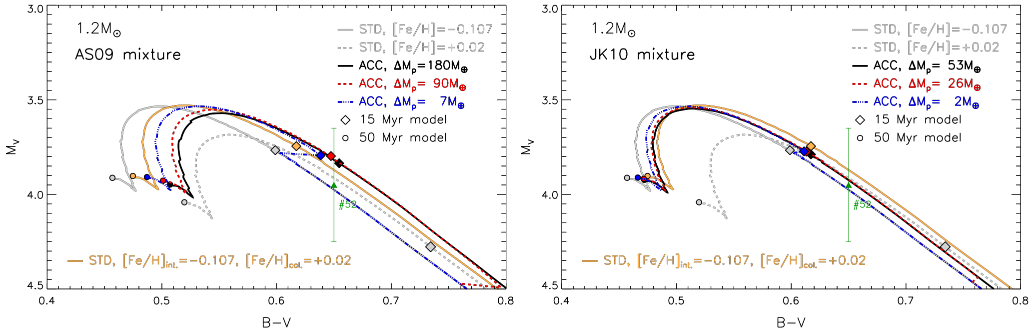

Fig. 2. Colour-Magnitude diagrams for models with and without planet ingestion episode with the AS09 (left panel) and the JK10 (right panel) planet chemical composition.

ity of about 34% and about 10% respectively. Such a metallicity change reflects on the properties of the stellar surface, such as the extension of the convective envelope and the stellar colours after the accretion.

Figure 1 shows the extension of the convective envelope as a function of the stellar ages for models with and without the planet ingestion episode in the case of AS09 mixture. The large variation of the surface metallicity obtained in the case of the AS09 mixture leads to an increase of the opacity in stellar envelope which produces a deeper convective envelope. Such an effect increases with the mass of the ingested planet. On the other hand the mild change of Z^{new} in the JK10 case leads to a very small variation of the convective envelope which is very similar to that of models without a planet ingestion episode.

Figure 2 shows the comparison between the evolutionary track of models with and without the planet ingestion episode in the colour-magnitude diagram, for planet with the AS09 and JK10 chemical composition. In the case of iron-poor planet (AS09, left panel), if a planet of $M_p = 180 M_\oplus$ ($t_0 = 10$ Myr) is ingested, the increase of the total metallicity produces an effective temperature reduction of about 120-150 K and a model about 0.05 dex redder than non accreting one. If a smaller planet is accreted (i.e. for larger t_0, namely 12 and 15 Myr) then the effect on the evolutionary track is smaller. Notice that the impact of the planet engulfment on the stellar models is still present long after the accretion episode, in particular when the star reaches the ZAMS position. The impact on the evolutionary track of a planet ingestion is smaller if iron-rich matter is accreted, as shown in right panel of Fig. 2. In this case only a small variation of the effective temperature (about 40 K) and of the colour (about 0.01 dex) in the most favourable case is expected. This analysis showed that a planet ingestion episode has a relatively large impact on the stellar surface chemical composition, but it might also affect the stellar structure in dependence of the planet characteristics.

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